

The Effect of Switch-Loading Fuels on Fuel-Wetted Elastomers

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ABSTRACT

The Office of the Secretary of the Defense (OSD), Advanced Systems and Concepts, established the OSD Assured Fuels Initiative, which aims to spark commercial production of clean fuels made from U.S. energy sources for use by the U.S. Military. The Department of Defense (DoD) will provide the “spark” by developing the fuel specifications needed, demonstrating and qualifying the use of these fuels in tactical ground vehicles, aircraft, and ships, and transitioning to the full-time use of these fuels in their fleets operating in the U.S. One such clean fuel, Fischer-Tropsch (FT) synthetic fuel, made using low-temperature FT technology, contains no aromatic compounds. This lack of aromatics, along with the lack of sulfur, are the key differences between a FT kerosene-based fuel and the petroleum-derived JP-8/JP-5 kerosene-based fuel that is the predominate bulk fuel used by the military’s air, ground, and marine fleets. [1, 2]¹ A series of experiments were done to determine effects to the fuel-wetted elastomers typically found in sealing applications throughout various fuel distribution systems of DoD equipment, to switching between fuel containing aromatics to fuel with no aromatics, a.k.a. “switch-loading”. One grade of nitrile studied exhibited large dimensional swings, as much as 8% volume change, upon fuel switch-loading. Such dimensional change presents potential for fuel leakage around the seals; this is especially true for older O-rings or gaskets that have taken a compression set. When transitioning to the use of FT fuels in DoD fleets, this risk of fuel leakage can be mitigated through the use of blends of FT kerosene with JP-8 or through identifying

susceptible sealing applications and replacing the elastomer components therein with new components and/or components made of less affected, more suitable elastomers.

INTRODUCTION

With the continued emergence of the global FT synthetic fuels industry, and the active business development and legislative activities in support of commercial FT fuels production in the U.S., the DoD, under the auspices of the OSD Assured Fuels Initiative, continues to target the goal to qualify FT fuel for use in its tactical ground vehicles, aircraft, and ships, and related equipment. Some of the work needed to attain this goal is already underway, in collaboration with the Department of Energy (DOE) National Energy Technology Laboratory (NETL), the Coordinating Research Council (CRC) Aviation Committee, various academic partners and their affiliated research arms, unaffiliated research institutes, original equipment manufacturers (OEMs), transportation industry stakeholders, FT technology providers, and FT fuels manufacturers. This work includes: (1) fuel specifications development, (2) laboratory, component, vehicle, and systems evaluations, (3) engine certifications, and (4) demonstrations. In preparing for demonstrations and qualification of FT fuels by the Army, investigations and lab evaluations by engineers at the Tank Automotive Research, Development, and Engineering Center (TARDEC) have been on-going to study the compatibility of FT fuel with the Army’s equipment. The response of petroleum fuel-wetted elastomers used in various sealing applications to FT Iso-Paraffinic Kerosene (IPK) containing no aromatics has been the focus of this work. FT IPK predominately consists of iso-paraffins, but also contains some normal paraffins. On the other hand, FT-derived synthetic crude consists of mostly normal

¹ Numbers between brackets refer to References found at the end of the document.

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paraffins; this waxy product requires further processing to produce and maximize yields of fuels having good low temperature properties.

Elastomer materials are used throughout fuel distribution systems of air and ground vehicles and equipment as seals, coatings, hoses and other various applications. These materials have varying degrees of resistance and sensitivity to fuels. Depending on the specific elastomeric compound, inclusive of fillers/plasticizers and curing, some change in properties, such as hardness, may result as the elastomer is exposed to the fuel. These changes do not typically result in application performance issues, but may when a dramatic change in the type of fuel occurs. It is generally known that aromatic species in hydrocarbon fuels are primary contributors to elastomer swelling. In the case of a seal, aromatic constituents in the fuel will cause seals made from certain affected elastomers to increase in volume (swell) as absorption of the aromatic solute takes place. In a likewise fashion, if that seal is then subjected to a fuel containing a greatly reduced level of aromatic solvents, the process may reverse itself and the seal may then decrease in size (shrink). Such a reduction in the size or volume of the seal may result in poor sealing performance and possibly even leakage of fuel. Some aged components may exhibit compression set that could more readily lead to leakage upon shrinkage of the seal, depending on the degree of compression set and other physical considerations.

Laboratory tests were conducted to determine changes to specimens made of various elastomeric materials upon immersion in fuels of varying aromatic composition. Many elastomeric materials are known to swell in the presence of aromatic hydrocarbons. [4-6] Based on initial test results, further immersion testing was done on acrylonitrile-butadiene, or "nitrile", specimens. [6] Nitrile is one elastomer particularly sensitive to changes in fuel aromatic composition and, historically, it is the most commonly used elastomer for seals. Finally, changes in nitrile specimens were studied as they underwent fuel "switch-loading" that switched them back and forth between two fuels of varying aromatic composition.

In addition to the lab evaluations, investigations were done to identify fuel-wetted elastomers in Army equipment. Then, based on type of elastomer, seal design, and specific function of the seal within the fuel distribution system, assessments were completed to gage the risk and impact of introducing fuels of significantly lower aromatic content than what is typical of current fuel.

LAB EVALUATIONS

Coupons and O-rings of selected elastomer materials were immersed in each fuel, at elevated temperature, for an extended time. Before immersion, and at several intervals thereafter, measurements were made and net

changes in mass, volume, and hardness (coupons only) were determined. For O-rings only, dimensional measurements were also made using an optical microscope and net changes in volume then determined.

ELASTOMER SPECIMENS

Elastomer N0674-70, a general purpose 70-durometer nitrile, was chosen for this study. A nitrile was selected as it is ". . . representative of today's diesel fuel systems and advanced technology diesel systems." [11] In addition, nitrile is representative of the types of elastomers found in Army ground and air, tactical and combat fuel systems of the existing fleet. [4] Finally, this nitrile was evaluated in earlier studies, where it exhibited significant responses to changes in fuel aromatic content, especially when compared to the fuel-resistant fluorinated carbon polymers. [4,6,12]

FUELS

Table 1 lists the five test fuels. "S-5" is from Syntroleum Corporation and is a high flash-point synthetic FT IPK with similar physical and chemical properties to JP-5 and JP-8, but not containing any aromatics, or any of the additives required for use in military equipment. [1-2, 7-8] JP-8/JP-5/Jet A-1 are designated the "single battlefield fuel" for use in military aviation turbine and diesel engines. [3] S-5 contains no aromatics. This is representative of synthetic fuels made from the synthetic crude derived from FT synthesis utilizing low reactor temperatures with either cobalt- or iron-based catalyst, as opposed to high temperature FT synthesis using an iron-based catalyst. Note that JP-5 is a "high flash point" JP-8, and could actually be shown as a JP-8 in Table 1.

Table 1. List of Test Fuels

<i>Fuel Name</i>	<i>Fuel Description</i>	<i>Sample ID No. (FL)</i>	<i>Aromatics, % V, (ASTM D 1319)</i>
S-5	FT IPK, 0% V aromatics	11741-03	0
S-5+10% A150	FT IPK + 10% V aromatics	--	11
JP-5	Jet fuel, 18% V aromatics	11891-04	18
ECD-1	ULSD, 19% V aromatics	11749-03	23
S-5 + 25% A150	FT IPK + 25% V aromatics	--	26

The two petroleum test fuels were a JP-5 fuel, provided by the U.S. Navy, and an Emission Control Diesel-1 (ECD-1) from the BP Refinery near Los Angeles. [9] The JP-5 contains approx. 18% V aromatics; the current specifications for JP-8 and JP-5 allow a maximum of 25% V aromatics, while there is no minimum

requirement. [7-8] ECD-1 is a California Air Resources Board (CARB) equivalent ultra-low sulfur fuel equivalent² No. 2 Diesel, with sulfur < 15 ppm and approximately 19% V aromatics. [9] The current specification for low sulfur diesel fuels in the U.S. allows up to 35% V aromatics. [10] More extensive property data for the test fuels is found in the Appendix.

ExxonMobil's petroleum-based Aromatic 150 Fluid ("A150"; FL-11755-03), was added to neat S-5 to produce the other two fuels used in this study, S-5+10%A150 and S-5+25%A150, with aromatic contents of 10% V and 25% V, respectively. The major aromatic species in A150 are shown in Table 2.

Table 2. Major Aromatic Species in Aromatic 150 Fluid ("A150")

This data provided by the DOE National Energy Technology Laboratory, GC-FID and GC-MS Methods.

Compound	Volume Percent (% V)
naphthalene	12.0
tetramethylbenzenes	22.0
ethyl-dimethylbenzenes	25.0
methylpropylbenzenes	8.3
pentamethylbenzene	1.9
methyl-methylpropylbenzenes	3.4
<i>Subtotal alkyl-substituted benzenes</i>	60.6
dihydromethylindene	3.0
methylindan	3.0
indane	0.7
Major Species Identified. Total	79.3

TEST PROCEDURE

Nitrile N0674-70 coupons (25×50×2.0±0.1 mm) cut from elastomer sheets, and N0674-70 O-rings (9.12-9.37 mm inner diameter × 1.70-1.85 mm cross-section diameter) were suspended at 40°C in glass vessels containing each of the test fuels. Measurements were made at 0, 3, 9, and 43 days to determine changes in specimen swell and hardness (coupons only) prior to conducting switch-loading tests. Just after 43 day measurements were done, specimens were immersed into the second fuel of the fuel switch-loading pairs as designated in Table 3.

Table 3. Switch-Loading Fuel Pairs

Fuel 1	Fuel 2
S-5	JP-5
S-5+10%A150	JP-5
S-5+10%A150	ECD-1
ECD-1	JP-5
S-5+25%A150	JP-5
S-5+25%A150	ECD-1

For the determination of swelling response, ASTM D 471 was followed and measurements were done on four specimens of each type. [13] Volume change due to swell was determined based on a water displacement technique. For measuring hardness, ASTM D 2240 was followed and measurements were done on three specimens. [13]

RESULTS: 43-DAY IMMERSION TESTS

The average coupon mass and volume change found after 43 days of immersion in various fuels at 40°C is shown in Figures 1 and 2, respectively. Likewise, for the O-rings, the average mass and volume changes are shown in Figures 3 and 4, respectively. Standard deviation bars are shown in all figures; nearly all standard deviations are small, some so small that their bars are barely visible in the figures.

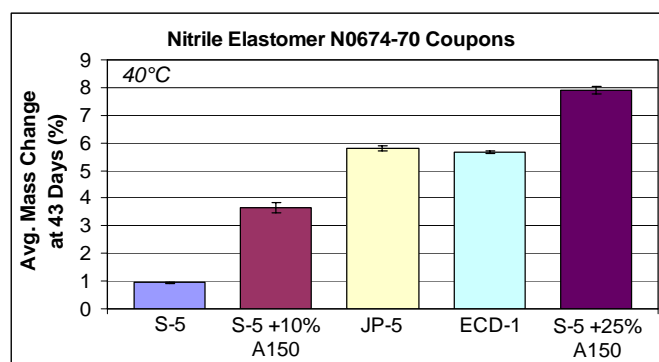


Figure 1. Average Mass Change (%) After 43 Days for Nitrile N0674-70 Coupons

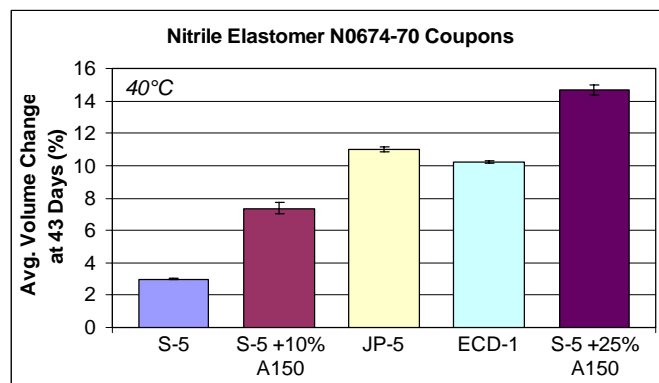


Figure 2. Average Volume Change (%) After 43 Days for Nitrile N0674-70 Coupons

² The term 'fuel equivalent' refers to fuels that meet emissions requirements without meeting fuel property requirements.

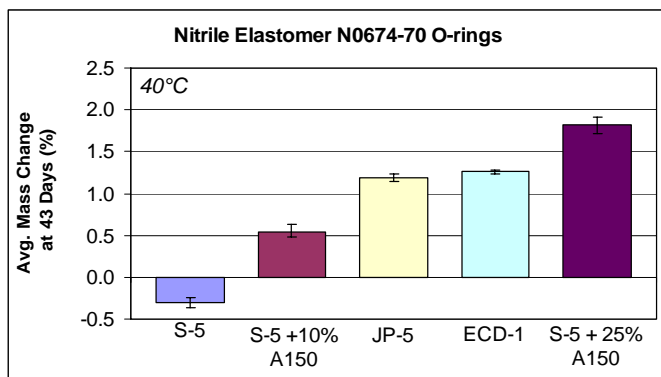


Figure 3. Average Mass Change (%) After 43 Days for Nitrile N0674-74 O-rings

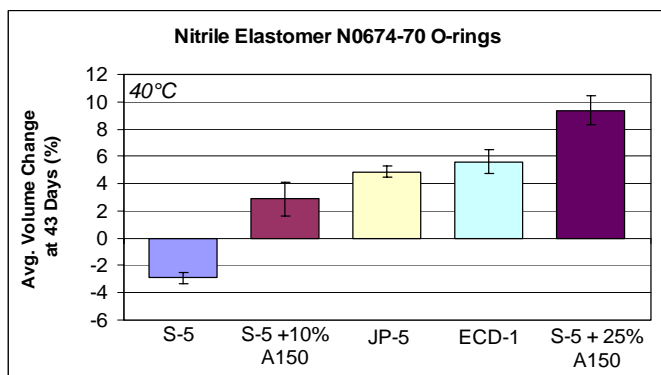


Figure 4. Average Volume Change (%) After 43 Days for Nitrile N0674-70 O-rings

The average hardness changes found for each specimen after 43 days of immersion in the various fuels at 40°C is shown in Figure 5.

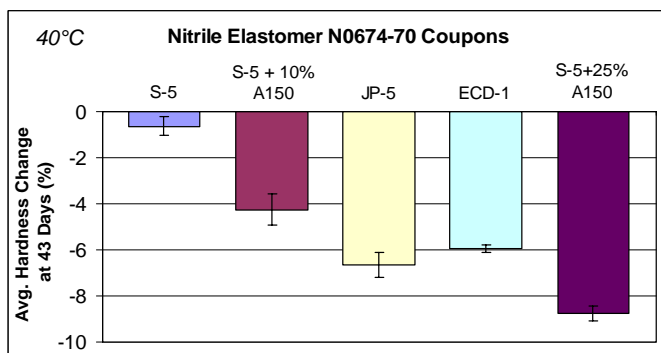


Figure 5. Average Hardness Change (%) After 43 Days for Nitrile N0674-70 Coupons

Nitrile N0674-70 coupons experienced swelling when immersed in each test fuel; the overall trend was increased swelling as the fuel aromatic content increased. Some interesting observations are made studying responses in more detail, particularly for coupons exposed to the petroleum-based fuels (JP-5 and ECD-1) versus S-5+25%A150. Coupons exposed to JP-5 reached a change in volume approaching that of coupons exposed to S-5+25%A150 (+11.0% and +14.7%, respectively), even though significantly less aromatics are present in JP-5 versus S-5+25%A150

(18% V and 25% V, respectively). On the other hand, coupons exposed to ECD-1 experienced slightly less change in volume to that of coupons exposed to JP-5 (+10.2% and +11.0%, respectively), even though the aromatic content of ECD-1 is similar to that of JP-5 (19% V and 18% V, respectively). These non-linear responses of swell for nitrile in these fuels (S-5+25%A150, JP-5, and ECD-1) can be attributed to differences in fuel composition other than just simply aromatic “content” (concentration); i.e., not only is the concentration of aromatics present a factor in the degree of swell, but so too is the specific type of aromatics, e.g., the degree of alkyl substitution.

The University of Dayton Research Institute (UDRI), in conjunction with the U.S. Air Force Research Laboratory (AFRL), conducted research and found that nitrile exhibits preferential absorption of fuel components in the order: aliphatics < aromatics < diaromatics < di-EGME. [14] Note that the latter component in this hierarchy, di-EGME, is not a naturally-occurring component in JP (Jet Propulsion) fuels, but rather a required additive in JP-8/JP-5 as a fuel system icing inhibitor. [7-8] Di-EGME, along with other components such as methyl phenols and methyl esters which do occur naturally in JP fuels, are polar compounds. As shown in the work by AFRL-UDRI, polar components in fuels, even at very low concentrations, *particularly di-EGME*, may significantly influence the swelling behavior of nitrile so as to make it “more easily swollen by the less polar components of the fuel such as the aromatics.” With this background, a plausible explanation is possible for the non-linear response in nitrile swell found in the TARDEC study. [15] Table 4 lists selected fuel components and indicates their presence in the test fuels. As shown, the JP-5 fuel used in this study does contain di-EGME (see also Appendix) in addition to aromatics, and would be expected to also contain other polar components. ECD-1 would also be expected to contain polar components; ECD-1 and S-5+25%A150 do not contain di-EGME, as deliberately added or as anticipated otherwise. Therefore, the anticipated effectiveness of these fuels in swelling nitrile would be JP-5>ECD-1>S-5+25%A150; the data generated in the TARDEC study supports this conclusion. There may be other factors relating to differences in aromatic composition, such as the degree of alkylation on the aromatic ring and the molecular weight of alkyl-substituted monoaromatic rings, which would also explain the relative swelling effectiveness of these fuels. In addition, absorption of aromatics may also enhance absorption of saturated hydrocarbons in the fuel into the elastomer. [14]

Table 4. Presence* of Selected Fuel Components in Test Fuels

Fuel Component	JP-5	ECD-1	S-5 + 25% A150
di-EGME	+		
Polars (excl. di-EGME)	+	+	
Diaromatics	+	+	+
Monoaromatics	+	+	+

* As detected in testing or as anticipated.

The results for equilibrium swell, expressed as % V change at days 7 and 43, between the UDRI and TARDEC studies are shown in Table 5. The tests were conducted with different nitrile compounds, and the duration of immersion and fuel temperature during immersion were different, so it is difficult to draw strong conclusions regarding similarities or differences between the results, nevertheless some statements can be made.

Table 5. Equilibrium Swell Results of Nitrile in Test Fuels¹

Unless otherwise noted, results reported as V% change from volume in air, as measured per water displacement method, ASTM D 471.

Fuel (% V aromatics)	UDRI Study Nitrile N-602, 7 days at 21°C	TARDEC Study Nitrile N0674-70, 43 days at 40°C		
	O-Rings	O-Rings	O-Rings (Calc.)²	Coupons
S-5 (0%)	1.7%	-2.9%	-4.0%	3.0%
S-5+A150 (10%)	2.0% ³	2.9%	5.0%	7.4%
JP-5/S-5 (10%)	7.5% ³	—		—
JP-5 (18%) ⁴	15.0%	4.9%	8.7%	11.0%
ECD-1 (19%)	—	5.6%	4.4%	10.2%
S-5+A150 (25%)	10.5%	9.4%	13.4%	14.7%

¹ The standard deviations for data in 2nd & 4th columns are shown in Figures 2 & 4, respectively; std. dev. for data in 1st column were not reported in reference cited; std. dev. for data in 3rd column are available through contact given at the end of this paper.

² Results shown are calculated from O-ring inner diameter (ID) and cross-section (CS) dimensions determined via a video microscope at ×10 magnification where volume (V) is $V = \frac{1}{4} \pi^2 \times CS^2 \times (ID + CS)$.

³ These values were interpreted from plots.

⁴ The JP-5 20% V aromatics level-UDRI study is slightly different than the 18% V aromatics-TARDEC study, even though the samples are from same Navy-provided sample lot.

In the TARDEC study, the size of the O-rings used were specified per SAE AS568-012, with as-manufactured dimensions called out for inner diameters of 9.12-9.37 mm and cross-sections of 1.70-1.85 mm, resulting in a range for O-ring volume (calculated), as-manufactured, of 77.16-94.75 mm³; the O-ring size used in the UDRI study was not reported. In the TARDEC study the net swell of the O-rings immersed in S-5 was negative (-2.9%), while in the UDRI study a +1.7% change occurred; however, in the TARDEC study the change for coupons was +3.0%. A notable difference is seen for the O-ring swell values in JP-5 fuel. In the UDRI study a +15.0% change was found, while in the TARDEC study a change of only 4.9% was measured; note, however, that in the TARDEC study a change of +11.0% was measured for the coupons.

In the TARDEC study, Nitrile N0674-70 O-rings experienced swelling when immersed in each test fuel, with the exception of neat S-5. Unlike the nitrile coupons tested, the O-rings exposed to S-5 actually decreased slightly in volume (shrank), by 2.9%, and had a slight corresponding decrease in mass (-0.3%). Differences in the TARDEC study between the volume changes for the coupons versus the O-rings might relate to the composition of the nitrile and the nitrile test specimen itself. Although both the O-rings and coupons are identified as being made of Nitrile N0674-70, they almost certainly were not produced from the same lot/batch of material (they were purchased from different suppliers), so there are may be some variations in composition from the material compounding process. In addition, the manufacturing processes employed are a factor in the resultant properties of an elastomer part. The coupon test specimens were fabricated (cut) from nitrile sheet material, which most likely was extruded, while the O-rings were molded. Still, the overall trend in nitrile swelling for the O-rings was similar to that found for the coupons, i.e., the greatest amount of swell was measured with S-5+25%A150 (+9.4% and +13.4% for O-rings, +14.7% for coupons).

According to coupon data, the most effective fuel in swelling, relative to aromatic content, occurred with JP-5 fuel (+11.0% swell), then ECD-1 (+10.2% swell), and finally S-5+25%A150 (+14.7% swell). This overall trend did not hold as true for the O-ring data. For O-ring data derived by the water displacement method, the swell in JP-5 was only +4.9% and in ECD-1 only +5.6%, as compared to the swell in S-5+25%A150 of +9.4%. For O-ring data derived from dimensional measurements, the swell in JP-5 was +8.7%, as compared to the swell in ECD-1 of only 4.6% and in S-5+25%A150 of +13.4%. In this case, the O-ring data supports JP-5 as being more effective in swelling than ECD-1, but not more so than S-5+25%A150.

Changes in durometer points were observed for all coupons after exposure to the fuels. At the end of 43 days, Nitrile N0674-70 coupons had decreases in durometer points in all fuels; i.e., the nitrile softened.

The trend was increased softness with increasing aromatic content of the fuel. The largest change was measured in coupons exposed to S-5+25%A150 with a change in durometer points of -8.7% at 43 days. In addition, the trend for swelling effectiveness of the test fuels, JP-5>ECD-1>S-5+25%A150, identified from coupon data, also held for softening effectiveness as indicated by coupon data (note: hardness data was not determined for O-rings since specimen geometry cannot accommodate this measurement).

RESULTS: SWITCH-LOADING TESTS

The nitrile N0674-70 coupons and O-rings responded to changing levels of aromatic content in the fuel as they were switched back and forth between the various fuel pairs. An example of this response, for the S-5/JP-5 fuel pair only, is seen in Figures 6 and 7³ for changes in nitrile mass and volume, respectively; other fuel pairs affected the nitrile specimens similarly. For instance, the volume change of the nitrile coupon in S-5 (Fuel 1) is approximately +3.0%. Upon switching to JP-5 (Fuel 2), the volume change increases significantly, to about +11.0%. Once the specimen was switched back into S-5, it decreased in volume, although to a level slightly lower, +1.0%, than that attained in the first immersion (+3.0%). At the next switch (back into JP-5), once again the nitrile increased in volume and reached +10.0%. On the final switch into JP-5, the nitrile reached near a +10.0% volume increase. Each fuel produced a unique level of nitrile swell (increase in mass and volume) depending on the aromatic content. The higher the level of aromatics in the fuel, the greater the nitrile swelled.

The swings in swell for O-rings switched between fuels were much smaller than for coupons as seen in Figures 6 and 7. It would seem that, since the surface area to volume ratio for O-rings is nearly twice that of the coupons, the diffusivity of the fuel into the specimen would be faster for O-rings versus coupons. The data indicate that the coupon gained nearly three times as much mass in the same amount of time as the O-ring; the specimen weight ratio is about 31:1 (coupon weight: O-ring weight.). The fact that the coupons apparently had a much greater uptake of fuel may be partially due to the fact that the coupon test specimens had exposed cut edges as they were fabricated (cut) from nitrile sheet material, while the O-rings had no exposed cut edges as they were molded; the diffusion of fuel into the coupon could have been more readily accommodated through its exposed, cut edges.

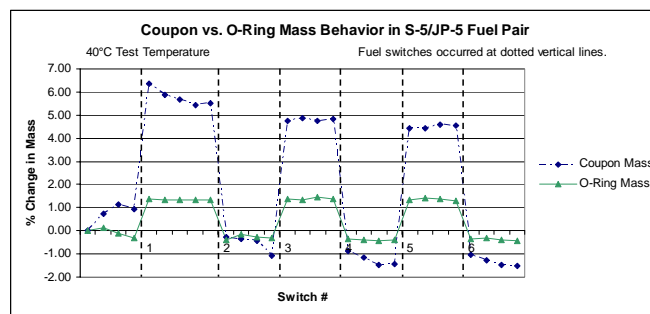


Figure 6. Comparison of Mass Percent Change Between Coupons and O-rings in S-5/JP-5

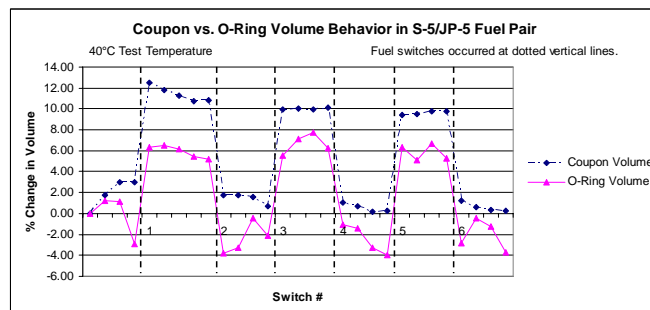


Figure 7. Comparison of Volume Percent Change Between Coupons and O-rings in S-5/JP-5

Data showed decreases in mass and volume for O-rings in S-5. Similarly, coupons in S-5 decreased in mass but not volume. At least the decrease in mass for both the O-rings and coupons suggests that the S-5 may be leaching something, such as fillers or plasticizers, out of the nitrile.

Change in Nitrile N0674-70 coupon hardness followed a predictable behavior. After the coupons' initial switch into petroleum fuels (Fuel 2), and then the next switch back into Fuel 1, they reached a hardness value slightly higher than their respective 43 day equilibrium values in Fuel 1. Hardness remained steady in the petroleum fuels (Fuel 2), while in Fuel 1 the coupons exhibited a unique level of hardness relative to the amount of aromatic in the fuel. The trend of lower hardness values with increasing aromatics content held for switches into Fuel 1, similar to the trends observed for changes in mass and volume.

Summaries of the results, for all fuel pairs, from the static switch-loading evaluation are shown in Figures 8 and 9³ for mass and volume changes, respectively; all changes are with respect to the initial mass or volume of the specimens in air prior to testing, and specimen repeatability, not shown in these figures, are available in original report. [15] These figures show the delta in mass or volume percent change between switch "0" and switch "1" for all six fuel pairs evaluated, and compare coupon data to O-ring data. This delta, between switch "0" and switch "1", is representative of the deltas found between subsequent switches as the response of the

³ Standard deviations for data shown in Figures 6 - 9 are available through contact provided at the end of this paper.

nitrile remained reasonably consistent as switches continued.

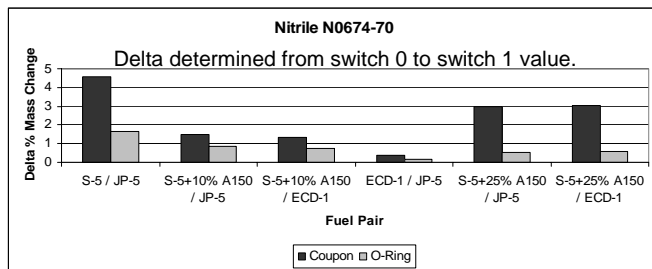


Figure 8. Delta in % Mass Changes of Nitrile N0674-70 for All Fuels Switch-Loaded

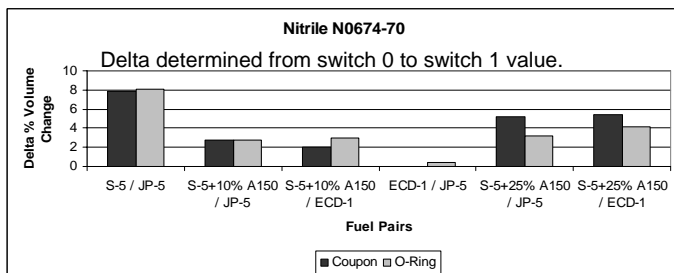


Figure 9. Delta in % Volume Changes of Nitrile N0674-70 for All Fuels Switch-Loaded

The swings in swell are generally greater for fuel pairs with larger differences in aromatic content, while they are smaller for fuel pairs with less difference in aromatic content. However, this is not entirely true. There is a slightly greater difference in aromaticities between the S-5+10%A150 and the petroleum fuels (JP-5: 18% V and ECD-1: 19% V) than between S-5+25%A150 and the petroleum fuels, yet S-5+25%A150 yielded significantly greater delta values. This is another indication of the non-linear relationship between the difference in percent aromatics and effective swell.

IMPLICATIONS OF INTRODUCING FUELS WITH LOWER AROMATIC CONTENT INTO ARMY EQUIPMENT

Introduction of FT fuels that are free of aromatics and polar components, such as a FT IPK like the S-5 fuel, into the existing DoD fleet presents the possibility of performance degradation from fuel leakage in some equipment. Fuel leakage may occur where elastomers sensitive to changes in fuel aromatic content, such as nitrile, are fuel-wetted (normally in contact with the fuel) and meant to contain or seal the fuel within the particular equipment's fuel distribution system. O-rings are an elastomer component configuration often used for this sealing function, although various other elastomer component configurations, such as gaskets or face-type seals, are also used. O-rings may either be used in static applications, where none of the adjoining components are in motion or in dynamic applications where an adjoining component is in motion.

O-rings and face-type seals are significantly different in the way they affect a seal. O-rings rely upon radial compression, or compression force, to prevent fluid flow. Face-type seals are loaded uni-axially, much like simple gaskets. If a face-type seal demonstrates a leak, it can be a simple matter to apply more force to the seal, especially if tightening bolts are used to hold the assembly together and they are accessible. When O-rings leak, additional radial force cannot be easily exerted onto the seal. For this reason, O-rings are generally designed for either an interference fit (i.e., a certain initial compressive force), ensuring the O-ring will always make contact with the mating surfaces, or the designer expects that the fluid will cause the O-ring to swell. In both cases, the O-ring elastomer will exhibit compression set over time – that is, the elastomer will “age” over time and undergo stress relaxation. As this relaxation occurs, the effective sealing (radial compression) force decays. At some point, the O-ring will fail to exert the force necessary to maintain a seal and must be replaced to re-attain original functionality.

O-ring designs need to take elastomer swelling into account as the O-ring comes into contact with fuel. Too much swell can lead to seal extrusion. In static applications, a swell of up to 50% volume change may be acceptable, while for dynamic applications, only up to 15-20% swell is considered acceptable. [16] In dynamic applications, swelling may lead to increased friction and wear, so less volume change can be tolerated. [17]

A sort of “worst case scenario” for an O-ring is when it has a high compression set, as is often the case with aged O-rings, and it undergoes “abnormal” shrinkage – this typically leads to seal failure, i.e., fuel leakage. The phenomenon of shrinkage is stated to be “abnormal” because in the case of conventional fuels (those derived from petroleum), some types of elastomeric materials typically swell (such as nitrile or fluorosilicone) or exhibit little or no swell (such as fluorocarbon elastomers). The abnormal shrinkage could take place upon either of two conditions. One condition could be when O-rings are allowed to “dry out”, that is, they are no longer fuel-wetted for an extended period of time. In this situation, some slight shrinkage may be expected to occur as fuel evaporates from the elastomer. Upon reintroduction of the fuel (petroleum-derived), some leakage may initially occur, but then will typically subside as the O-ring again swells enough to exert the needed compressive force to seal. This very situation was reported to be common when ground vehicles are drained of fuel for shipment to forces deployed overseas. This information was shared with TARDEC engineers during an October 2006 visit to staff of the 127th Wing of the Air National Guard, Selfridge Air Reserve Base, at Selfridge Air National Guard Base north of Detroit. Once the vehicles arrive, often after an extended period of transit time and possibly even high temperature conditions (which would have favored fuel evaporation from the O-rings and heat ageing of the O-rings), it is not uncommon to have fuel leaks upon reintroduction of JP-8 into the vehicles. The

typical corrective action is to note the fuel leaks, tightening assemblies where possible to stop the leaks, and then to wait a few days and recheck for leaks. In most cases, the leaks have dissipated, presumably as the O-rings have swelled again, and the vehicles are put into service.

The other condition that would cause abnormal shrinkage of O-rings would be the introduction of a fuel that does not cause an elastomer to swell, but rather to shrink. O-ring shrinkage could result, depending on the elastomer material, upon introduction of a FT synthetic fuel free of constituents found in conventional fuels that cause some elastomer materials to swell, namely aromatics and polar compounds. As little as 3-4% shrinkage of an O-ring (3-4% decrease from original volume), is possibly enough to result in fuel leaks as an O-ring pulls away from sealing surfaces. [16]

The Army has a large, diverse fleet of ground vehicles, helicopters, and equipment (e.g., generator sets) that burn kerosene and/or diesel fuel. This equipment can range from reasonably old to relatively new. As such, the fuel systems in this equipment can be fairly different, with a variety of critical seals and a wide array of fuel-wetted seal elastomer materials. In addition, the Army is responsible for inland fuel storage, distribution and handling equipment, which expands the lists of critical seals and fuel-wetted seal elastomer materials.

To assess risk of fuel leakage upon introduction of a FT IPK, investigations were done to identify fuel-wetted elastomers in Army equipment. This identification process did not encompass all fuel-wetted elastomer components found throughout the vast expanse of Army equipment, but does represent a large cross-section, and as such, is a good start. Based on type of elastomer, seal design, and specific function of the seal within the fuel distribution system, assessments were completed to gage risk of introducing fuels with significantly lower aromatic content than that typical of current fuel.

GROUND EQUIPMENT

The Southwest Research Institute (SwRI™), San Antonio, TX, was engaged to study the fuel systems of a subset of the existing Army fleet. This subset consists of high density and mission-critical combat and wheeled vehicles, and ground support equipment. Specifically, they determined the engines used in each application and the type of fuel system on each engine. This was further broken down to type of fuel pump and injector. The elastomer seals on these pumps and injectors were identified by part number and material. Schematic drawings were studied to determine locations and specific functions of the seals within the fuel pumps. Using this information, an assessment was done to determine the risk of leakage from introduction of an aromatic-free fuel such as FT IPK, and what the impact

would be to equipment operability if that leakage were to occur.

Table 6 reveals only a portion of the elastomer types identified in fuel pumps and injectors of fuels systems in the SwRI study. As shown, fluorocarbon elastomers are prevalent and this is good news. Most fluorocarbon elastomers are known to be fairly inert to most fluids. In several studies, including those by TARDEC, fluorocarbon elastomer materials did not swell or shrink significantly in various test fuels, whether petroleum-based JP fuel or fully-synthetic FT IPK. [4-6,12] Therefore, risk of fuel leakage due to shrinkage if a FT IPK were introduced is low for seals made of fluorocarbon elastomeric materials. Nitrile and butadiene elastomers are also listed in Table 6. Nitrile, a co-polymer of acrylonitrile and butadiene, is affected by various fluids, including fuels. It is known to have high swelling tendencies in aromatic fluids. Significant nitrile swelling in test fuels containing aromatics was confirmed in TARDEC evaluations, as was the tendency of nitrile to shrink when first immersed or switched into an aromatic-free fuel such as FT IPK. [6, 12] So, risk of fuel leakage increases for elastomeric seal components made of nitrile upon introduction of FT IPK.

Table 6. Elastomers Identified in Some Army Ground Equipment Fuel Pumps & Injectors

Elastomer	Seal Component Description
<i>Stanadyne DB2 Rotary Inj. Pump – GEP 6.2L, 6.5L</i>	
Fluorocarbon elastomer	Seal (driveshaft)
	Gasket (timing window cover)
	O-Ring (cam ring/hyd head)
	O-Ring (plate lock)
	Seal (transfer pump)
	O-Ring (shaft control assembly)
	O-Ring (drain plug)
	O-Ring (plug, advance screw)
	Seal (advance plunger)
	O-Ring (screw, head locating)
	O-Ring (pressure regulator assy)
	Seal (governor control cover)
Fluorosilicone	Seal (driveshaft)
Nitrile (BUNA N)	O-Ring (governor adj. screw)
<i>Bosch In-Line Injection Pump – Cummins 6CTA 8.3</i>	
Butadiene (BUNA)	O-Ring (barrel assembly)
	O-Ring (barrel assembly)
	O-Ring (delivery valve holder)
Nitrile (BUNA N)	Washer, Seal (fuel gallery)
<i>DD Unit Self-Metering Injector – Detroit Diesel 8V92T</i>	
Fluorocarbon elastomer	O-Ring
<i>Hydr.-Actuated Electr. Unit Inj. Caterpillar 3116, 3126B</i>	
Fluorocarbon elastomer	O-Ring
	O-Ring

Similar discussions regarding fuel leaks from fuel-wetted seals in fuel systems of ground vehicles and introduction of a lower aromatic-content fuel has already occurred in the commercial sector. In August 2005, Cummins, Inc. issued one of their "Early Warning" notifications. [18] This notice was to inform the field of a potential fuel pump leak for some Cummins engines using the listed fuel systems if a customer switches to Ultra Low Sulfur Diesel (ULSD) fuel after using Low Sulfur Diesel (LSD) fuel. More specifically, it identified the potential for leakage from the lift pump between the bracket and the lift pump body or at the electrical connector. It went on to state that the gasket between the lift pump body and the bracket was made of nitrile and that if a fuel switch was made from LSD to ULSD, this nitrile could shrink and would no longer seal, thus creating a fuel leak. Typically, a severe hydrotreatment is employed to remove sulfur from diesel fuel to produce ULSD, with 15 ppm max. sulfur allowed, rather than the less-severe hydrotreating or simply hydrodesulfurization used to produce LSD, with 500 ppm max. sulfur allowed. This more severe hydrotreating will tend to also reduce the aromatic content. A Texas refiner, Valero, produces a type of ULSD with well under the 10% aromatics ($\approx 5\%$) allowed in CARB diesel. [19] Thus, a fuel switch from LSD to ULSD effectively introduces a fuel of lower aromatic content – analogous to switching from a JP-8 fuel containing aromatics to a FT IPK with no aromatics.

Diesel fuel producers, such as Chevron and BP, have also commented on fuel leaks as a result of switching from LSD to ULSD. Chevron Products Company, also in August of 2005, issued a "Technical Bulletin" entitled "Fuel Leaks from Seals of Vehicles Using Low Sulfur Diesel Fuel". [20] In this bulletin Chevron stated that some vehicle owners beginning to use ULSD were reporting fuel leaks similar to the fuel leaks that occurred in the 1990's when LSD was introduced. Chevron went on to explain that during the 1990's, the leaks occurred at points where elastomers (O-rings) sealed joints in the fuel system, at that during 1993-94, the most common occurrences were injector fuel pump leaks. They also stated that this phenomenon can affect some engines that are older than ten years, but that some newer ones experienced the problem as well. Chevron said that these types of fuel leaks could again occur once the majority of fuel supplies are switched to ULSD. However, they anticipated that only a very small fraction of the vehicles may be affected. They stated that "The evidence to date suggests the problem is linked to a change in the aromatics content of the S15 ultra low sulfur diesel fuel, to seal material and age of the material". In summing up past experience, the bulletin stated that "the common denominator is expected to be nitrile rubber (Buna N) seals that have seen long service at high temperatures. High temperatures have a tendency to accelerate seal aging." Chevron recommended consumers contact the equipment manufacturer for advice on a replacement elastomer for the seals that leaked and concluded with the statement that newly replaced seals should not develop a leak.

BP was the first oil company to introduce 50 ppm sulfur ULSD in Australia. [21] In early 2001, BP reported numerous consumer claims of engine fuel leakages. At that time, BP commented that "Some older equipment has experienced problems with low sulphur diesel fuel. The problem is that the top seals on some rotary fuel pumps have started leaking." They went on to explain that 90% of the complaints are from Japanese light-duty diesels with rotary pumps, mostly pre-1993. Furthermore, they stated that "No significant problems have been reported with in-line pumps such as those used in heavy-duty diesel engines such as heavy trucks, earth-movers, generators and boats", and that "No significant problems have been reported with rotary pumps as used on tractors and farm machinery." However, it was reported that some Australian mining companies apparently experienced several problems with certain heavy-duty engines. In responding to consumers, the BP message was that "the process of removing the sulfur changes the composition of the fuel. The refinery cannot produce the low-sulfur fuel any other way. Once the seals on the [vulnerable] fuel pumps are replaced, the problem will not re-occur."

A recent presentation made by a fuel quality expert summarized a previous investigation regarding diesel-related problems at the time of the October 1, 1993 introduction of low sulfur diesel fuel. He noted that fuel systems that experienced leakages used seals made of Buna N, while those with Viton®⁴ did not. [22] Viton elastomers are a class of fluorocarbon elastomers (sometimes just referred to as "fluorocarbon") that include various dipolymer, terpolymer, and copolymer compounds. [23] Other factors of seals that leaked were noted as: (1) reduced elasticity due to age (old), (2) typically high mileage or hours, (3) exposure to high temperature, (4) thermal cycling, and (5) shrinkage (reduced swelling). His presentation explained that "aged nitrile seals might be more susceptible because old seals are less pliable and elastic. When new they change shape and fill the cavity maintaining a seal." The explanation continued, stating that if seals are hardened (loss of plasticizers) and have "compression set", that changes in aromatic content of the fuel might have an effect on sealing. The expert also noted that "most, if not all manufacturers, responded by eliminating nitrile rubber seals and replacing them with fluorocarbon seals." It was also noted that replacement of the seals solved the leakage problem in most cases and that "after 1994, OEMs should have advised existing fleets and implemented design changes for future models."

SwRI has been assessing the potential negative impacts from fuel leakage for those seals most at risk according to the type of elastomer material identified; that is, they are making this assessment for seals made of elastomeric materials identified as from the Acrylonitrile-

⁴ Viton is a name trademarked by DuPont Performance Elastomers L.L.C.

Butadiene family (nitrile, NBR rubber, or Buna N are commonly used names). The seals were classified according to whether the leak at that seal would be external or internal to the equipment's fuel system. In addition, seals were also identified as to whether they are static or dynamic seals; dynamic seals would typically be less tolerable of shrinkage than static seals, just as they are less tolerable of swell than static seals. Seals yielding an internal leak will result in fuel leakage that remains within the equipment's fuel system and recirculates to the fuel tank. Internal leaks would likely result in loss of internal pressure in the fuel injection pump, and this could lead to an alteration in timing. Altered timing might, in turn, result in poor engine performance and a reduction in fuel efficiency; also, in an engine running less smoothly and, if neglected, might prevent start-up of the engine or stop it while running. [24] If a leak would result in fuel exposure outside of the fuel system, it would be classified as an external leak. Generally, these are associated with the fuel injector pump inlet and outlet lines. Inlet lines are not normally under high pressure and, therefore, would not cause much of a spill in the event of a leak. Fuel in the outlet lines is under high pressure. In this case, fuel could be rapidly lost from equipment, would result in a loss of engine power, and could possibly jeopardize the ability to operate the equipment as long as planned prior to the next refueling. It could also create a safety hazard.

One example of impact assessment done by SwRI is for the single nitrile O-ring identified in the Stanadyne Rotary Injection Pump Model DB2 (see Table 6) used in the High Mobility Multi-purpose Wheeled Vehicle (HMMWV) Series GEP 6.2L/6.5L. This particular O-ring is a static seal and any leak would be external. SwRI learned that the equipment manufacturer provides a fluorocarbon elastomer replacement for this seal. Another impact assessment was done for the nitrile washer that seals the fuel gallery of the Bosch In-Line Injection Pump of the Cummins 6CTA 8.3 engine found in the M939 Series 5-Ton Truck. This seal application is also static and any leakage would be external. Because this seal is a nitrile-over-molded steel compression washer, if a leak were to develop, it could probably be stopped by tightening the assembly. Based on all the impact assessments SwRI has completed so far, about 70% of the seals most at risk would develop external leaks. Furthermore, only about 15% of the seals most at risk are dynamic, and in all cases these would develop internal leaks.

FUEL STORAGE, DISTRIBUTION AND HANDLING (SDH) EQUIPMENT

The U.S. Military's ability to fight and sustain operations on the battlefield is dependent on the capacity to supply fuel promptly to the warfighter. The U.S. Army utilizes a network of fuel SDH equipment to transport fuel from the point of receipt to the skin of the vehicle/equipment. The network is comprised of three primary systems: mobile fuel tankers, storage bladders/cells, and distribution

equipment. Network equipment configurations are specific to support a particular need. Configurations include the Inland Petroleum Distribution Systems (IPDS), Forward Area Refueling Equipment (FARE), and the Tactical Petroleum Training Module; these systems are engineered to be compatible, maneuverable, and reliable. [25-31] Similar to the tactical vehicles, these systems were originally designed to function with JP-8 and diesel as the primary fuels. As such, a thorough assessment was performed to evaluate and identify potential vulnerabilities (whether compatibility or functionality) of Army SDH systems when exposed to low or very low aromatic fuels. Much of the assessment was performed by reviewing published equipment technical manuals containing detailed descriptions and illustrations of individual components, and physical inspection of components. The following sections highlight many of the key elements identified in each system.

Mobile Fuel Tankers

Mobile fuel tankers are utilized by the military to transport, deliver and dispense fuel. Although the capacity of the fuel tankers varies, the basic components and requirements are quite similar. Each fuel tanker is equipped with a diesel-powered centrifugal pump responsible for loading and unloading the fuel. Although these diesel pumps are often not specified for each fuel tanker, they are similar to pumping units used in tactical ground vehicles. Therefore, these pumps may have issues with fuel-wetted elastomers depending on type and configuration of the pump. The majority of fuel tankers are equipped with a filter/water separator assembly as described in MIL-PRF-52666 [31,32]. The separator assembly contains several fuel-wetted elastomers at the fuel nozzle and sample connection outlet; these elastomers serve as couplings and often a means of tightening the coupling assembly is present, thus any leaks in these areas could possibly be stopped by further tightening of the assembly. Similarly, a fuel hose can be connected to the fuel tanker via quick-disconnect camlock couplings, which utilize an elastomer to mechanically seal the coupling to a fuel nozzle. Finally, the hose material itself is an elastomer and will be in contact with fuel. However, this elastomer component only serves to contain the fuel, rather than to act as a seal, and its function will not be impacted by the type of swelling and shrinkage discussed herein. Hoselines will be discussed in more detail in a following section.

Note that hose reels involve seals, including O-rings, which may leak if lower aromatic content fuels are introduced.

Tanker Ballistic Protection System (TBPS)

The exterior surface of fuel tankers is sometimes reinforced with a TBPS. The TBPS utilizes a fuel tank self-sealing system (FTSS) to prevent fuel leakage

following a small-arm projectile impact to the fuel tank. The FTSS allows the projectile to penetrate through its surface, but self-seals within seconds to minimize fuel leakage. Currently, two types of FTSS systems are being developed. The self-sealing mechanism is achieved through a combination of mechanical properties of the rubber being penetrated and the fuel interaction with the polymer. Change in fuel aromatic composition may affect the self-sealing mechanism, thus FTSS performance for use of FT fuels should be assessed in ballistic testing.

FUEL BLADDERS

Mobile fuel tankers unload fuel into the fuel system supply point (FSSP). The FSSP is comprised of coated fabric fuel bladders, which can have a storage capacity from 500 to 60,000 gallons [30]. The coated fabrics are composed of either a nitrile or polyurethane material. Although nitrile and polyurethane are known to swell more when exposed to high aromatic fuels than low aromatic fuels, this effect has no bearing on the effectiveness of the fuel bladders to store fuel. Therefore, the fuel bladders can be expected to demonstrate equal functionality with low and high aromatic fuels.

Similar to the mobile fuel tankers, FSSP bladders require a diesel-powered centrifugal pump to load and unload the fuel, as well as nozzle/hoses and quick-disconnect camlock couplings [30].

FUEL CELL BLADDERS

Fuel cell bladders are utilized by numerous military aviation fuel systems as a lightweight, onboard fuel storage system. The fuel cell bladders are designed to self-seal following a small arm projectile impact, and are required to be crashworthy per MIL-DTL-27422C [33]. Fuel cell bladders are composed of four or more primary layers. The innermost layer interfaces with the fuel at steady state is often composed of a nitrile rubber. The exterior layer of the fuel cell bladder is a nylon retainer, which helps maintain the structure and shape of the fuel cell bladder. In between these layers are numerous crisscrossing layers of an interwoven nylon fabric, each separated by a layer of sealant ply. The ply is an elastomeric laminate containing a sealing composition comprised of a fuel-insoluble polymer dispersed in a solvent [34,35]. The ply reacts immediately when exposed to fuel causing the sealant ply to become semi-mobile and coagulate to the surfaces of the displaced fabric [34,35]. The ply has been described as a natural gum rubber. Early patents of the technology describe the ply as a mixture of diisopropyl benzene (80-93%), dibutylphthalate (2-10%), and polymethacrylate (5-10%). [34] At steady state, the innermost nitrile layer acts as a fuel barrier and prevents fuel from traveling through the interwoven fabric and prematurely swelling the sealant ply.

Self-Sealing Mechanism

Both the fuel cell bladders and FTSS have shown to be effective at self-sealing holes left by the penetration of small arm projectiles. The primary self-sealing mechanism can be attributed to the mechanical properties of the polymer after being penetrated followed by a secondary chemical reaction between the fuel and polymer. Initially, the polymer provides resistance to projectile penetration based on its puncture resistance. After puncture resistance is overcome, the projectile transmits an impact force pulse and frictional heat to the polymer. The elastic properties of the polymer allow the material to yield (or 'give') and deform, rather than be destroyed, allowing the projectile to penetrate through the polymer. After the force pulse is exhausted, the polymer elastically reforms to its original state; however, mechanical losses may occur and the elastic deformation to reformation transition may not be completely efficient resulting in pores (or channels). As a result, a secondary reaction is required to completely seal the system. Secondary self-sealing is instigated by fuel contacting and swelling each layer of the fuel cell bladder, thereby sealing any potential pore not sealed mechanically. The fuel-instigated swelling most rapidly occurs in the sealant ply.

Self-sealing polymer systems (fuel cell bladders, TBPS, etc.) are being evaluated to determine their self-sealing capability when exposed to low/no aromatic fuels. Preliminary testing has shown the sealant ply and the micro-expansion beads (of FTSS) swell when exposed to JP-8/DF-2 and FT fuels with no aromatics. The amount of swell for each fuel has not been quantified due to limitations in volume measuring techniques for these micro-sized polymers. The final assessment of self-sealing will require a ballistic demonstration.

DISTRIBUTION EQUIPMENT

Fuel distribution equipment describes a wide assortment of equipment, hoses, couplings, gaskets, elbows, and valves required to distribute fuel to/from storage to the skin of the vehicle. The Assault Hoseline System (AHS) and Rapidly Installed Fluid Transfer System (RIFTS) are two fully capable distribution systems. Fuel-wetted elastomers are ubiquitous in the distribution equipment. The following is an evaluation of the critical subgroups identified.

Coupled Pipelines

Two types of coupled pipelines are utilized in the fuel distribution infrastructure: steel and aluminum. Steel pipes are grooved at both ends, and utilize a split-ring coupling and gasket for sealing. [25] Similar, aluminum pipes are grooved at both ends and are coupled with a hinged snap-joint utilizing either a one-piece or integral two-piece split-seal gasket as illustrated in Figure 10. [25] Both the split-ring and snap-joint couplings and gaskets are designed to seal under pressure and

vacuum. [25] The hinged coupling is designed to allow a 2% deflection between joints. [25] Based on these facts, these couplings are expected to remain sealed regardless of the fuels aromatic content.

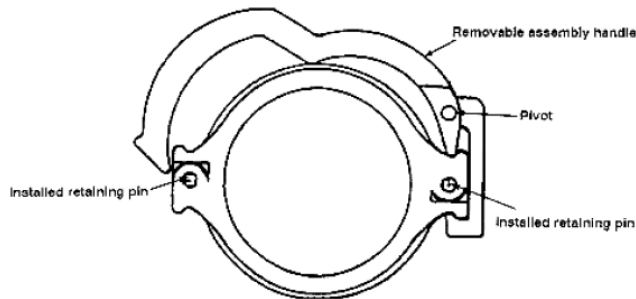


Figure 10. Hinged Snap-Joint Coupling [25]

Pipeline Valves and Fittings

Pipeline valves are required to control and direct the fuel flow through the system. Valves utilized in the military distribution system include: gate, check, plug, ball, pressure-reducing, pressure control, pressure-regulating, and thermal-relief valves. Although these valves have elastomeric components, the majority of these valves utilizes a mechanical process to control fuel flow through a pipe, and elastomer shrinkage would not result in fuel leakage. The gate valve may be the most notable exception. A gate valve is used to allow or deter flow in the pipeline or a tank. The valve appears to utilize several fuel-wetted elastomer gaskets and seals to maintain a seal as shown in Figure 11. [25] Reducing the volume of gate valve gaskets and seals may increase its probability of leakage.

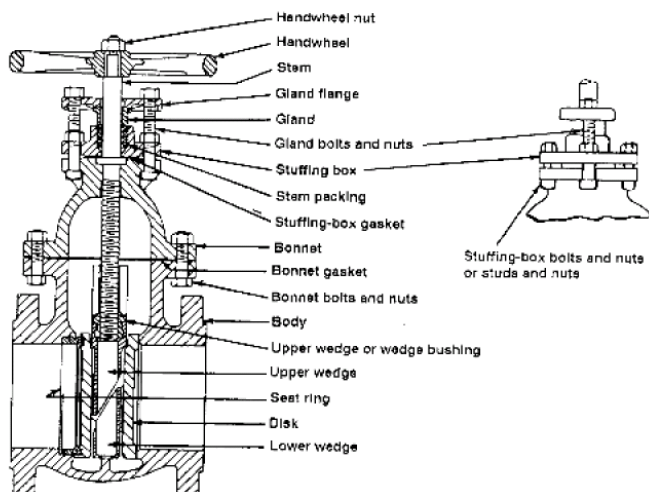


Figure 11. Nonrising-Stem Gate Valve [25]

Pipe-Repair Accessories

Two main clamps, split-leak and overcoupling-leak, are used to temporarily repair leaking pipes and couplings

are used to repair leaks. The split-leak clamp is fitted around the leaking pipe using a saddle, elastomeric gasket, and stirrups as seen in Figure 12. The gasket is positioned over the leak, and tightened mechanically via the stirrups. Similarly, the overcoupling-leak clamp applies sealing force through mechanical tightening. The elastomer gasket ensures the seal via the mechanical force applied by the stirrups, thus elastomer shrinkage should not result in fuel leakage. [25]

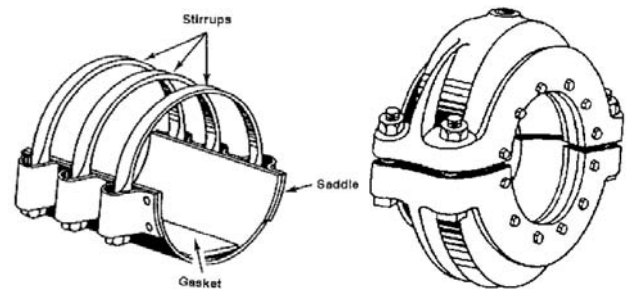


Figure 12. Split-leak Clamp (left). Overcoupling-leak Clamp (right). [25]

CONCLUSION

Key goals of the OSD Assured Fuels Initiative are for DoD to qualify the use of FT synthetic fuels in tactical ground vehicles, aircraft, and ships, and then to begin the full-time use of these fuels in their U.S. based fleets. FT synthetic fuel, made using low-temperature FT technology, contains no aromatic compounds, unlike the petroleum-based fuels used by the military today. Based on laboratory testing and equipment assessments completed by TARDEC and SwRI, and also based on experience in the commercial sector with the introduction of lower aromatic content diesel fuels, if a neat (100%) FT IPK synthetic fuel were introduced into the existing fleet of Army ground combat/tactical vehicles, ground support equipment, and fuel storage, distribution and handling equipment, some fuel leaks should be expected. At particular risk of fuel leakage is equipment wherein fuel system fuel-wetted seals:

- are made of nitrile (Buna N, acrylonitrile-butadiene), and
- have been in service a long time and, therefore, inevitably have some degree of compression set, especially if service temperatures have been elevated or thermal cycling has occurred.

Fuel leaks that develop may be able to be stopped simply by tightening of the assemblies containing the seal components, as is possible. In cases where tightening is not possible, such as is generally the case with O-rings, the seal should be replaced. Although it would be possible to replace a nitrile seal with a new nitrile seal to stop the leak, a better choice would be to use a seal made of a material such as a fluorocarbon

elastomer that is less affected by changes in fuel composition. With the on-going and expanding evolution from use of conventional fuels (derived from petroleum) to use of alternative fuels, such a choice would be wise. A good example of this type of improvement is the replacement fluorocarbon elastomer seals for the nitrile seals originally specified for the HMMWV rotary pump with the GEP 6.2L/6.5 L engine.

Other fuel leaks may develop that are not readily noticeable. These would be those seal failures that result in internal leaks. Most susceptible in this category of "internal leakers" are dynamic seals made of the most at-risk elastomers such as nitrile/Buna N/ acrylonitrile-butadiene. Even though these leaks would not be externally apparent, they could result in some loss of performance, so these seals should also be replaced, again preferably with a seal that is less affected by changes in fuel composition.

Still under investigation by TARDEC is a specialized application of elastomer composites as "self-sealing" materials, such as are used for aviation fuel cell bladders. Preliminary work indicates that the performance of these materials may still be acceptable with use of a neat FT fuel. However a final determination of the self-sealing capability will require a ballistic demonstration.

One means of introducing the use of FT fuels into DoD fleets based in the U.S. is through the use of blends of FT IPK with JP-8 or JP-5. An extensive analysis of such fuel blends was completed by TARDEC and published in a 2006 SAE paper. [36] In this case, specifying some minimum level of aromatic content for the final fuel blends would be a means of introducing the use of FT IPK into existing DoD equipment and avoiding the fuel leakage issue. In this scenario, blends could be used while, over the course of routine maintenance and upgrading, replacement and introduction of new equipment could allow change-over to seals made of the desired elastomers.

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APPENDIX

Properties of S-5, JP-5 and ECD-1 Fuels

Property, Units	ASTM Test Method	S-5	JP-5		ECD-1
		Analysis by Army-TARDEC FL-11741-03	Analysis by Army-TARDEC FL-11981-04	Analysis by Navy ¹ FF-03-033	Analysis by SwRI FL-11749-03
Appearance	D 156				
Flash point, °C	D 56 (D 93)	62	61	(62)	(48)
Freezing point, °C:	D 5972 (D 2386)	-50	-47	(-50)	(-8)
Saybolt Color	D 156	30	22	26	N.A.
Total Sulfur, wt %	D 2622 (D 4294)	<1 ppm	0.11	(0.12)	<0.001
Distillation temperature, °C:	D 86				
Initial boiling point		183	181	176	180
10% recovered		194	190	188	204
20% recovered		201	193	193	213
50% recovered		219	207	206	247
90% recovered		254	236	235	314
Final boiling point (end point)		267	251	252	343
residue, % vol.		1.3	1.3	N.A.	1.4
loss, %		0	0.9	N.A.	N.A.
Density at 15°C, kg/m ³	D 1298 (D 4052)	0.764	0.803	(0.803)	0.821
Calculated Cetane Index	D 976 ² (ASTM D 4737)	69.5/67.3 (74.0)	46.0/46.0 (47.7)	N.A.	52.6/N.A. (53.6)
Aromatics, % vol. (% wt.)	D 1319 (D 5186)	<1 ³	18.4	19.8	-19.3
Kinematic Viscosity, mm ² /s	D 445				
at -20°C		6	4.7	4.8	N.A.
at 40°C			1.4	N.A.	2.18
Total Acid Number, mg KOH/g	D 664 (D 3242)	0.0014	<0.001	(0.003)	<0.01
Total Water Content, %	D 6304	0.0019	0.005	N.A.	0.0125
Conductivity, pS/m	D 2624	1	5	N.A.	N.A.

Notes:

¹ Analysis provided by the Navy showed presence of Fuel System Icing Inhibitor, di-EGME, at 0.16% vol. as determined by ASTM D 5006.

² Results shown are for Equation 1 / Equation 2 calculated values.

³ Internal method (GC-AED).